

Two new V-type asteroids in the outer Main Belt?¹

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ABSTRACT

The identification of basaltic asteroids in the asteroid Main Belt and the description of their surface mineralogy is necessary to understand the diversity in the collection of basaltic meteorites. Basaltic asteroids can be identified from their visible reflectance spectra and are classified as V-type in the usual taxonomies. In this work, we report visible spectroscopic observations of two candidate V-type asteroids, (7472) Kumakiri and (10537) 1991 RY16, located in the outer Main Belt ($a > 2.85$ UA). These candidate have been previously identified by Roig and Gil-Hutton (2006, Icarus 183, 411) using the Sloan Digital Sky Survey colors. The spectroscopic observations have been obtained at the Calar Alto Observatory, Spain, during observational runs in November and December 2006. The spectra of these two asteroids show the steep slope shortwards of $0.70\ \mu\text{m}$ and the deep absorption feature longwards of $0.75\ \mu\text{m}$ that are characteristic of V-type asteroids. However, the presence of a shallow but conspicuous absorption band around $0.65\ \mu\text{m}$ opens some questions about the actual mineralogy of these

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two asteroids. Such band has never been observed before in basaltic asteroids with the intensity we detected it. We discuss the possibility for this shallow absorption feature to be caused by the presence of chromium on the asteroid surface. Our results indicate that, together with (1459) Magnya, asteroids (7472) Kumakiri and (10537) 1991 RY16 may be the only traces of basaltic material found up to now in the outer Main Belt.

Subject headings: Asteroids, composition

1. Introduction

Basaltic asteroids are small bodies connected to the processes of heating and melting that may have led to the mineralogical differentiation in the interiors of the largest asteroids. Therefore, a precise knowledge of the inventory of basaltic asteroids may help to estimate how many differentiated bodies actually formed in the asteroid Main Belt, and this in turn may provide important constraints to the primordial conditions of the solar nebula.

In the visible wavelengths range, the reflectance spectrum of basaltic asteroids is characterized by a steep slope shortwards of $0.70\ \mu\text{m}$ and a deep absorption band longwards of $0.75\ \mu\text{m}$. Asteroids showing this spectrum are classified as V-type in the usual taxonomies (e.g. Bus & Binzel, 2002).

A few years ago, most of the known V-type asteroids were members of the Vesta dynamical family, located in the inner asteroid belt –semi-major axis $a < 2.5\ \text{AU}$ –. This family formed by the excavation of a large crater (Thomas et al., 1997; Asphaug, 1997) on the surface of asteroid (4) Vesta, which is the only known large asteroid –diameter $D \sim 500\ \text{km}$ – to show a basaltic crust (McCord et al., 1970).

Nowadays, however, several V-type asteroids have been identified in the inner belt but outside the Vesta dynamical family (Burbine et al., 2001; Florczak et al., 2002; Alvarez-Candal et al., 2006). Basaltic asteroids have also been found in the middle Main Belt – $2.5 < a < 2.8\ \text{AU}$ – (Binzel et al., 2006; Roig et al., 2007), as well as among the Near Earth Asteroids (NEA) population (McFadden et al., 1985; Cruikshank et al., 1991; Binzel et al., 2004; Duffard et al., 2006). Recent works (Carruba et al., 2005, 2007; Nesvorný et al., 2007; Roig et al., 2007) provide evidence that many of these V-type asteroids may be former members of the Vesta family, that reached their present orbits due to long term dynamical evolution. The exception is asteroid (1459) Magnya, the only basaltic object so far discovered in the outer belt – $a > 2.8\ \text{AU}$ – (Lazzaro et al., 2000). This asteroid is too far away from the Vesta family and it is also too big – $D = 20\text{--}30\ \text{km}$ – to have a real probability

of being a fragment from the Vesta’s crust (Michtchenko et al., 2002).

Beyond the existence of (4) Vesta and the V-type asteroids related to the Vesta dynamical family, the paucity of intact differentiated asteroids and of their fragments observed today in the main belt is an strong constraint to the formation scenario of basaltic material. The sample of iron meteorites collected in the Earth indicates that they would come from the iron core of dozens of differentiated parent bodies. However, there are very few olivine-rich asteroids (classified as A-type) which are assumed to come from the mantle of differentiated bodies, and only one asteroid, (1459) Magnya, is known to sample the basaltic crust of a differentiated parent body other than (4) Vesta. Finally, the other Main Belt asteroid families, which formed from the disruption of over fifty $10 < D < 400$ km asteroids, show little spectroscopic evidence that their parent bodies were heated enough to produce a distinct core, mantle and crust (Cellino, 2003).

Aiming to establish if other V-type asteroids might be found together with (1459) Magnya in the outer belt, thus giving support to the existence of a differentiated parent body in that part of the belt, Roig & Gil-Hutton (2006) used the five band photometry from the 3rd release of the Sloan Digital Sky Survey Moving Objects Catalog (SDSS-MOC; Ivezić et al., 2001; Jurić et al., 2002) to identify candidate V-type asteroids. Among 263 candidates that are not members of the Vesta dynamical family, Roig & Gil-Hutton found five possible V-type asteroids in the outer belt: (7472) Kumakiri, (10537) 1991 RY16, (44496) 1998 XM5, (55613) 2002 TY49, and (105041) 2000 KO41. However, these findings need to be confirmed by accurate spectroscopic observations.

The aim of this work is to describe the visible spectroscopic observations of two of these candidates: (7472) Kumakiri and (10537) 1991 RY16. Our goal is to provide a more reliable taxonomic classification of these asteroids indicating that *they would the second and third basaltic asteroids discovered up to now in the outer belt*. Our observations also reveal certain peculiarities of their spectra that deserve special attention in future studies. Last but not least, our results help to validate the approach of Roig & Gil-Hutton (2006) to predict V-type asteroids. It is worth recalling that a similar study has been performed by Roig et al. (2007), who used visible spectroscopic observations taken at the Gemini Observatory to confirm the classification of two candidate V-type asteroids in the middle belt: (21238) 1995 WV7 and (40521) 1999 RL95.

In Sect. 2, we describe the observations and the reduction procedures. In Sect. 3, we present and discuss the results obtained. Finally, Sect. 4 is devoted to conclusions.

2. Observations

Low resolution spectroscopy of (7472) Kumakiri and (10537) 1991 RY16 were obtained on November 14, 2006, as part of a 4 nights observational run, using the Calar Alto Faint Object Spectrograph (CAFOS) at the 2.2m telescope in Calar Alto Observatory, Spain. The prime aim of the run was to characterize V-type asteroids inside and outside the Vesta family. Asteroid (7472) Kumakiri was observed again on December 29, 2006, using the same instrument and telescope, under Director’s Discretionary Time (DDT). Table 1 summarizes the observational circumstances.

CAFOS¹ is equipped with a 2048×2048 CCD detector SITE-1d (pixel size 24 μm /pixel, plate scale 0.53"/pixel). We used the R400 grism allowing to obtain an observable spectral range between 0.50 and 0.92 μm . To remove the solar component of the spectra and obtain the reflectance spectra, the solar analog stars HD 191854, HD 20630 and HD 28099 (Hardorp, 1978) were also observed at similar airmasses as the asteroids. In order to estimate the quality of each night, at least two solar analogs were observed per night and we verified that the ratios between the corresponding spectra show no significant variations. Bias frames, spectral dome flat fields and calibration lamps spectra were also taken in each night to allow reduction of the science images. Spectrum exposures for each asteroid were splitted in two exposures at two different slit positions, A and B, separated by 20" (the width of the slit was 2.0"). The observations were performed with the telescope tracking at the proper motion of the asteroid. Hence by subtracting A from B and B from A, a very accurate background removal is achieved. Finally, standard methods for spectra extraction were applied.

3. Results and discussion

The reflectance spectra of (7472) Kumakiri and (10537) 1991 RY16 are shown in Figs. 1 and 2. Both spectra show a steep slope shortwards of 0.70 μm and a deep absorption band longwards of 0.75 μm . Using the algorithm of Bus (1999), we determine that the spectra can be classified as V-type. Figure 1 show that our observations are compatible with the spectra of previously known V-type asteroids (gray lines) taken from the SMASS survey (Bus & Binzel, 2002) and the S3OS2 survey (Lazzaro et al., 2004). Figure 2 show the good agreement between the five band photometry of the SDSS-MOC (black lines) and the observed spectra. It is worth noting that the values of maximum and minimum reflectance prevents to attribute to these spectra other taxonomic classification, like R-, O- or Q-type.

¹See <http://www.caha.es/alises/cafos/cafes22.pdf> for more details.

In view of this, (7472) Kumakiri and (10537) 1991 RY16 may be considered, together with (1459) Magnya, the only V-type asteroids discovered up to now in the outer belt.

Notwithstanding, the spectra of (7472) Kumakiri and (10537) 1991 RY16 show a shallow absorption feature around 0.60-0.70 μm that has never been reported before in V-type asteroids. This feature is more evident in the spectrum of (10537) 1991 RY16. After the its identification in the November 14 observations, and excluding possible reduction artifacts or solar analogs problems, we requested Director Discretionary Time (DDT) for another observational run on December 29. Only the spectra of (7472) Kumakiri was able to be observed during this run, confirming the presence of the absorption band. Nevertheless, the band in the spectrum of (10537) 1991 RY16 has also been observed independently by Moskovitz et al. (2007).

To analyze this band, we rectified the spectra by subtracting a linear continuum in the interval 0.55 and 0.75 μm and then fitted several polynomials of different degrees. This allowed to determine the center of the band at 0.63 ± 0.01 μm and the FWHM of ~ 0.1 μm (e.g. Fig. 3).

The origin of this absorption band is unclear. Such kind of bands are usually believed to arise from the $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ charge transfer absorptions in phyllosilicate (hydrated) minerals (Vilas & Gaffey, 1989; Vilas et al., 1993). However, it is difficult to explain the presence of a hydrated mineral in the surface of a basaltic object, because the heating and melting that produce the basalt also eliminate any traces of water.

It is known that pyroxene crystals Fe^{2+} cations do not show any absorption bands in the spectral region from 0.56 to 0.72 μm . Therefore, the origin of the observed band might be related to other impurity cations like Mn^{2+} , Cr^{3+} , and Fe^{3+} , usually located in the M1 site of terrestrial and meteorite orthopyroxenes (Shestopalov et al., 2007). In particular, broad spin-allowed bands of trivalent chromium around 0.430-0.455 μm and 0.620-0.650 μm have been observed in both reflectance and transmitted spectra of Cr-containing terrestrial ortho and clinopyroxenes (see Cloutis, 2002), as well as in diogenite reflectance spectra (McFadden et al., 1982). Cr^{3+} cations also give spin-forbidden bands near 0.480, 0.635, 0.655, and 0.670 μm but they do not give absorptions near 0.57 μm .

Cloutis (2002) specifically found that Cr^{3+} gives rise to an absorption band near 0.455 μm and a more complex absorption feature in the 0.65 μm region. However, changes in the grain size of the pyroxenes may have an effect on the depth of these absorption bands (Cloutis and Gaffey 1991; Sunshine and Pieters 1993). Therefore, the presence of specific absorption bands can be taken as an evidence for the presence of a particular cation, but the characteristics of these bands (depth and width) are probably not reliable enough to constrain

the cation abundance (Cloutis 2002). For example, the grain size may be responsible of the different band depth observed between the spectra of (7472) Kumakiri and (10537) 1991 RY16. The slight differences in the band profile between the November and December spectra of (7472) Kumakiri might be attributed to different rotational phases².

Another interesting feature observed in our spectra is that the band center of the major absorption feature at 0.90 μm is displaced to larger wavelengths. In our spectra, this region is the noisiest but using different polynomial fits it was possible to estimate the center of the band nearer to 0.92-0.93 μm . This behavior may also be attributed to the presence of chromium on the surface. Actually, Cloutis and Gaffey (1991) suggested that the Cr-rich pyroxene samples in their study have the two major absorption features (i.e. the one centered at 0.9 and the one centered at 1.9 μm , respectively) displaced to larger wavelengths than expected, relative to their Fe contents. These authors also presented the predicted *versus* actual wavelength position of the major Fe^{2+} absorption band center in the 1 μm region, and this center is closer to 0.92 μm than to 0.90 μm . Therefore, the observational evidence points to a possible Cr-rich basaltic composition on the surfaces of (7472) Kumakiri and (10537) 1991 RY16.

Concerning the dynamical behavior of these two asteroids, Table 2 lists their proper elements and diameters, as well as those of (1459) Magnya. The three asteroids are too small to be differentiated bodies by themselves, they are quite spread in proper elements space and do not belong to any of the asteroid dynamical families identified in the outer belt. Therefore, they are likely to be fragments from more than one differentiated parent bodies. Nevertheless, at variance with (1459) Magnya, (7472) Kumakiri and (10537) 1991 RY16 evolve very close to the non linear secular resonance defined by the combination $g_0 + s_0 - g_5 - s_7 \simeq 0$, where g_i and s_i represent the frequencies of the perihelion ϖ and node Ω , respectively ($i = 0$ for asteroid, $i = 5$ for Jupiter, $i = 7$ for Uranus; see Milani & Knežević, 1992). A 50 My simulation of the orbits of these two asteroids, including gravitational perturbations from the four major planets, indicate that they have quite stable orbits showing a slow circulation of the angle $\varpi_0 + \Omega_0 - \varpi_5 - \Omega_7$. Although this may be just a coincidence, a dynamical connection between (7472) Kumakiri and (10537) 1991 RY16 cannot be ruled out and should be addressed by more detailed studies.

²We have verified that these differences cannot be related to observation/reduction problems, since we do not find any differences between the spectra of the solar analog stars used in the different nights.

4. Conclusions

We presented visible spectroscopic observations of two asteroids, (7472) Kumakiri and (10537) 1991 RY16, located in the outer belt. The main goal of our work was to show that these observations are compatible with the V-type taxonomic class. Therefore, these bodies would constitute the second and third basaltic asteroids discovered up to now in that part of the Main Belt.

However, the presence of a shallow absorption band in the spectra around $0.65\ \mu\text{m}$ opens some questions about the actual mineralogy of these two asteroids. This band is likely to be related to the presence of Cr^{3+} cations, and provides evidence for a possible a Cr-rich basaltic surface.

The spectroscopic similarities among the two asteroids, together with some shared dynamical properties, point to the idea of a common origin from the breakup of a differentiated parent body in the outer belt. Further studies, including near infrared (NIR) spectroscopic observations, are mandatory to better address these issues.

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Table 1: Observational circumstances for the targets: Universal Time (UT), heliocentric distance (r), geocentric distance (Δ), phase angle (ϕ), visual magnitude (V), airmass and total exposure time (T_{exp}).

Asteroid	UT	r [AU]	Δ [AU]	ϕ [deg]	V [mag]	airmass	T_{exp}
November 14							
(7472) Kumakiri	03:25:00	2.920	2.123	13.5	16.6	1.037	3400 sec
(10537) 1991 RY16	00:05:08	3.040	2.053	1.8	17.1	1.091	4000 sec
December 29							
(7472) Kumakiri	21:48:52	2.873	1.901	3.8	15.9	1.094	3600 sec

Table 2: Proper elements and sizes of V-type asteroids in the outer belt. For (1459) Magnya, the last column gives the diameter from Delbo et al. (2006). For (7472) Kumakiri and (10537) 1991 RY16, the diameter was computed assuming an albedo of 0.40.

Asteroid	a_p [AU]	e_p	$\sin I_p$	D [km]
(1459) Magnya	3.14986	0.2183	0.2651	17.0 ± 1.0
(7472) Kumakiri	3.01033	0.1372	0.1562	8.5
(10537) 1991 RY16	2.84958	0.1023	0.1101	7.3

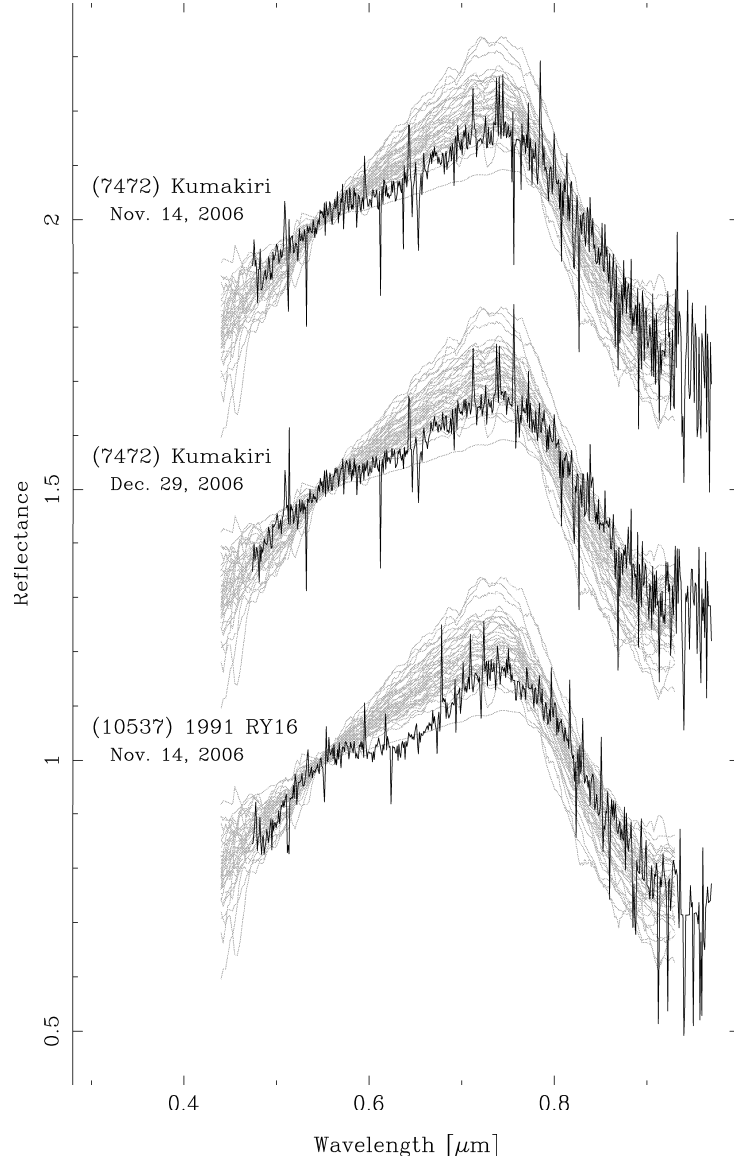


Fig. 1.— Reflectance spectra of (7472) Kumakiri and (10537) 1991 RY16 (black lines) compared to the spectra of several known V-type asteroids taken from the SMASS and S3OS2 surveys (gray lines). The spectra are normalized to 1 at $0.55 \mu\text{m}$ and shifted by 0.5 units in reflectance for clarity. To remove the solar contribution, we have used the solar analog HD 191854 in the November 14 observations and the solar analog HD 28099 in the December 29 observation.

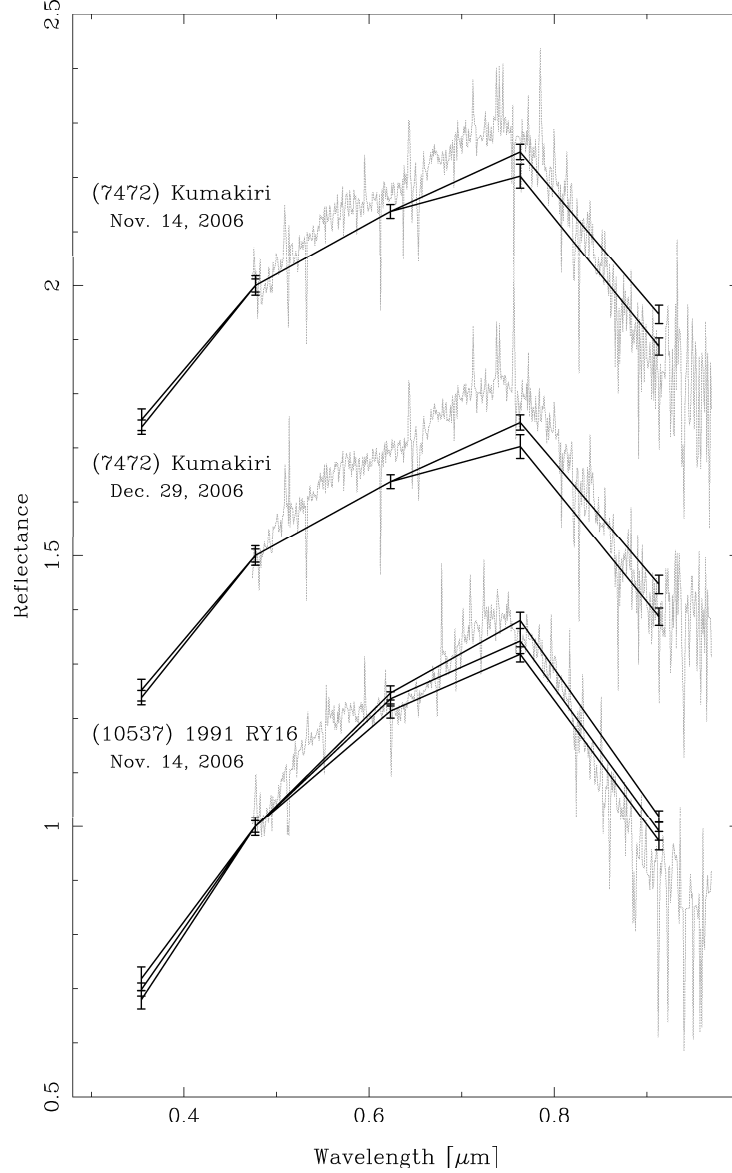


Fig. 2.— Reflectance spectra of (7472) Kumakiri and (10537) 1991 RY16 (gray lines) compared to the photometric observations of the SDSS-MOC (black lines). The spectra are normalized to 1 at $0.477 \mu\text{m}$ (i.e. the center of the g band in the SDSS photometric system), and shifted by 0.5 units in reflectance for clarity. The errors in the SDSS-MOC fluxes are less than 3%.

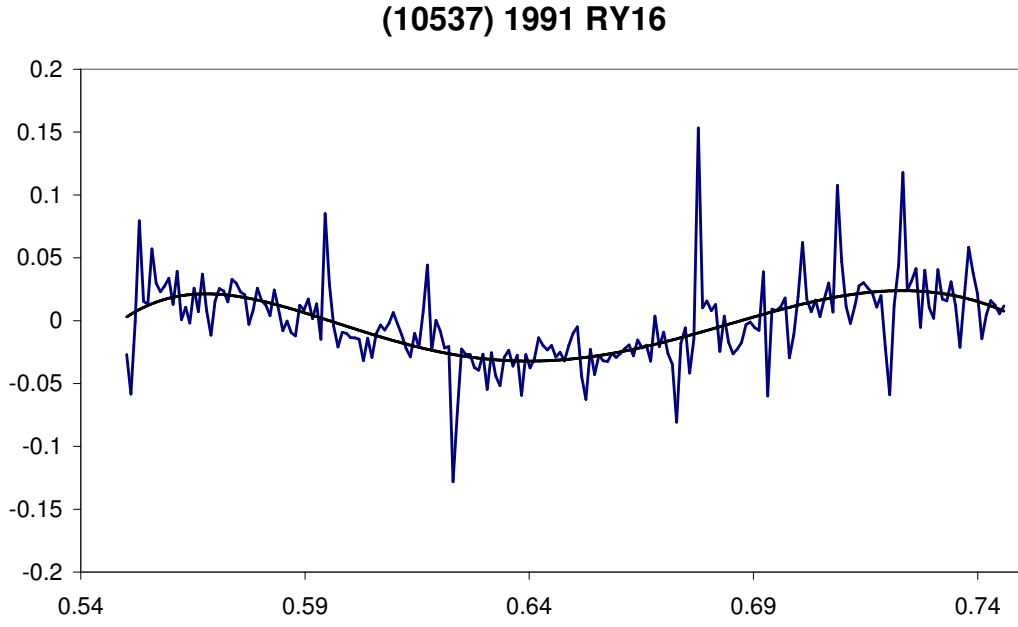


Fig. 3.— Reflectance spectrum of (10537) 1991 RY16 in the 0.55-0.75 μm interval. The spectrum has been rectified by subtracting a linear continuum in this interval. From a polynomial fit (thick line), the center of the absorption band is detected at 0.63 μm with a FWHM of 0.1 μm .